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By J. F. Scoville

GENERAL ELECTRIC

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GENERAL ELECTRIC Co.,
Waynesboro, Va.

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SUMMARY

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This is the second quarterly report for the "Study of Capacitors for Static Inverters and Converters".

The objectives of this study are: (1) to establish capacitor AC characteristics and ratings for reliable operation in aerospace static inverter and converter applications; and (2) to facilitate the proper capacitor selection to minimize volume and weight consistent with maximum equipment performance and reliability.

A need for this study was influenced by the significant capacitor volume, weight, power loss and reliability factors in static inverters and converters particularly on space vehicles where these factors are at a premium.

General Electric's Specialty Control Department in Waynesboro, Virginia is conducting this study.

This report covers the work accomplished from November 16, 1963 through February 16, 1964 and contains:

a) Results of the state-of-the-art capacitor survey.

b) Capacitor values selected for experimental testing.

c) Experimental test plans and objectives. Author

INTRODUCTION

Capacitors being studied are limited to those suitable for use in aerospace static inverters and converters operating in a space environment. The inverter ratings for this study are 115/200 Volt, 3 Phase, 400 cycles, 0.1 to 10.0 kilowatt output with the input voltage ranges from 25 to 105 Volt DC.

The need for the "Study of Capacitors for Static Inverters and Converters" was influenced by the stringent requirements imposed on capacitors by the operating nature of the equipment and environment.

In static inverters, appreciable heat generation within capacitors is caused by input voltage ripple having frequencies of several kilocycles, commutating current pulses of approximately 5 kilocycles and output harmonic current. Heat transfer from the capacitors is generally limited to conduction across the mounting surface to radiator systems on space vehicles. There is a lack of adequate alternating current data and characteristics for capacitors in aerospace inverter applications that could result in appreciable penalties in weight and reliability factors.

The study is divided into four (4) phases: (1) Define Capacitor State-of-the Art Survey; (2) Conduct Capacitor State-of-the-Art Survey; (3) Experimental Testing; and (4) Capacitor Evaluation and Recommendations'

During the first quarterly report period the Capacitor State-of-the Art Survey was defined and initiated.

This is the second quarterly report of the work accomplished between November 16, 1963 and February 16, 1964. During this period, the second phase of the study, "Conducting the Capacitor State-of-the-Art Survey", was completed and the third phase, "Experimental Testing", was initiated.

1.0 Capacitor State-of-the-Art Survey

1.1 Purpose

A survey was made of all known capacitor vendors to determine the recommended capacitor sizes and types for the specified capacitor ratings listed in Appendix A. These capacitor ratings, for aerospace static inverter and converter applications in this study, were established during the first quarterly report period.

1.2 Survey Evaluation Criteria

The following criteria were used in establishing the state-of-the-art for the specified capacitors in the survey:

A) Volume to capacitance ratio
B) Weight to capacitance ratio
C) Volume to energy storage ratio
D) Cost to energy storage ratio

One other criterion, power factor to thermal resistance ratio or resistance to heat conductivity, could not be used effectively since the power factor at the frequencies of interest were not available.

1.3 Results of Survey

Engineering specifications for the capacitor ratings used in the survey were forwarded to thirty (30) capacitor vendors. Six (6) of the thirty (30) furnished formal technical and cost proposals in response to the survey. Information obtained from contact with five (5) additional capacitor vendors proved valuable in determining the state-of-the-art for the capacitors.

1.3.1 Commutating Capacitors

The following four (4) types of capacitors were recommended by capacitor vendors for the commutating capacitor applications:

A) Metallized polycarbonate film
B) Polycarbonate film and foil
C) Paper-Mylar and foil
D) Paper and foil

The evaluation criteria variations encountered in the survey were:

A) Volume to capacitance ratio of:

0.22 to 1.85 in^3/ufd for the 35 and 65 Volt ratings
1.05 to 4.8 in^3/ufd for the 105 Volt rating

B) Weight to capacitance ratio of:

0.015 to 0.18 pounds/ufd for the 35 and 65 Volt ratings
0.058 to 0.34 pounds/ufd for the 105 Volt rating

C) Volume to energy storage ratio of:

44.5 to 411 in^3/joule for the 35 and 65 Volt ratings
85 to 374 in^3/joule for the 105 Volt rating

D) Cost per energy storage ratio of:

173.5 to 1145.0 dollars/joule for the 35 and 65 Volt ratings
114.5 to 1050.0 dollars/joule for the 105 Volt rating

Cost to energy storage ratio figures are considered only as figures of merit because capacitor prices were based on small quantities which may include some developmental engineering costs.

From information obtained in the survey, polycarbonate film and foil capacitors exhibit dissipation factors, in 25°C ambient with 120 cycles/second voltage, of 0.1 to 0.15% compared to 0.3 to 0.4% for metallized polycarbonate film capacitors.

1.3.2 A.C. Filter Capacitors

Capacitor vendors recommended the following four (4) types of capacitors for the A.C. filter capacitor applications:

A) Metallized polycarbonate film
B) Polycarbonate film and foil
C) Paper-Mylar* and foil
D) Paper and foil

Evaluation criteria variations encountered were:

A) Volume to capacitance ratio:

0.21 to 5.35 in^3/ufd for the 135 V rms ratings
0.5 to 7.65 in^3/ufd for the 270 V rms rating

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B) Weight to capacitance ratio:

0.018 to 0.33 pounds/ufd for the 135 V rms ratings
0.035 ro 0.535 pounds/ufd for the 270 V rma rating

C) Volume to energy storage ratio:

10.3 to 29.6 in^3/joule for the 135 V rms ratings
6.5 to 15.6 in^3/joule for the 270 V rms rating

D) Cost to energy storage:

27 to 45.8 dollars/joule for the 135 V rms ratings
11.8 to 62.4 dollars/joule for the 270 V rms rating

Again the cost to energy storage ratio figures are considered figures of merit because capacitor prices were based on small quantities which may include some developmental engineering costs.

1.3.3 D.C. Filter Capacitance

Recommendations for the D.C. filter capacitor applications included three (3) types:

A) Sintered tantalum

B) Tantalum foil

C) Polycarbonate film

Reservations concerning the specified peak to peak ripple voltages of 10 per cent of the D.C. voltage ratings accompanied the vendor recommendations for usage of tantalum electrolytic capacitors.

Slightly different evaluation criteria are used for the D.C. filter capacitors. The volume and weight to Volt-capacitance ratios were favored because the volume to capacitance for electrolytics varies approximately with voltage, whereas film capacitors rated at 50 Volts or below generally do not.

The volume to voltage capacitance ratios determined from the survey for these types of capacitors are:

Type	Cubic Inches/Volt-Microfarad
$125^{\circ}C$, Tantalum porons anode	$3.0-4.0 \times 10^{-5}$
$125^{\circ}C$, Tantalum foil	$11.0-13.0 \times 10^{-5}$
Polycarbonate film	$100-185 \times 10^{-5}$

Only $125^{\circ}C$ tantalum capacitors were considered in the survey to enable temperature derating for reliability purposes.

The effective series resistance (ESR), in $25^{\circ}C$ ambient and with 120 cycle/second voltage, is within the same order of magnitude (i.e., 1 to 10 ohms) for both types of tantalum capacitors. The ESR of polycarbonate film capacitors is at least one order of magnitude smaller than the tantalum electrolytics.

Weight to voltage-capacitance ratio for these three types of capacitors are:

Type	Pounds/Volt-Microfarad
Sintered Tantalum	$2.5-10.0 \times 10^{-6}$
Tantalum Foil	$5.0-16.8 \times 10^{-6}$
Polycarbonate Film	$87.5-265 \times 10^{-6}$

Volume to energy storage ratio variations are:

Type	Cubic Inches/joule
Sintered Tantalum	0.8 to 1.8
Tantalum Foil	0.75 to 4.06
Polycarbonate Film	44.5 to 120.0

The cost per energy storage ratio was not established from the survey because of incomplete cost and technical proposals from vendors. Reservations concerned with ripple voltage contributed to the incomplete proposals.

2.0 Selection of Capacitors for Experimental Testing

Capacitor selection for experimental tests was based on the following considerations:

A) Degree of compliance to the capacitor specifications

B) Low volume and weight to capacitance ratios

C) Low dissipation or power factor

D) Adequate temperature capability to enable temperature derating for reliability purposes

The capacitor survey was conducted with specifications for several ranges of capacitances and voltages as listed in Appendix A. However, economy is realized, while accomplishing the objectives of the study, by selecting minimum capacitance values listed in the specifications for the experimental tests. Packaging of larger capacitance values will be influenced by the power factor of the capacitor, which is a function of temperature, frequency, voltage waveform, and materials.

2.1 Commutating and A. C. Filter

Two of the four capacitor types recommended for the commutating and A.C. filter applications were selected for evaluation in the experimental tests. These are: a) Metallized polycarbonate film; and b) Polycarbonate film and foil.

The other two types recommended, paper/foil and paper-Mylar/foil, have a small cost advantage over polycarbonate dielectric capacitors, but they have larger power factors.

Metallized polycarbonate film capacitors with capacitance values of 2 to 3 microfarads and D.C. voltage ratings of 200 and 400 Volts were purchased from four (4) vendors.

Polycarbonate film and foil capacitors having capacitance values from 1 to 5 microfarads and D.C. voltage ratings of 200, 400 and 600 Volts were purchased from four (4) vendors.

A few metallized paper capacitors with capacitance values of 2 to 3 microfarads and D.C. voltage ratings of 200 and 400 Volts were selected for a comparative basis evaluation. Metallized paper capacitors by comparison with metallized polycarbonate have an approximate volume advantage of 25 per cent. However, they have an appreciable power factor disadvantage. These paper capacitors were purchased from two (2) vendors.

Other film type capacitors that were not considered for experimental test evaluation are:

A) Teflon*--These capacitors have adequate temperature capabilities and low dissipation factors but the size, weight and cost penalties compared with polycarbonate or paper capacitors offset any advantages.

B) Mylar--Capacitors of this type are comparable to the size and weight of polycarbonate capacitors but have appreciably larger power factors between 85°C and 125°C.

C) Polystyrene--These capacitors have characteristics that are comparable or better than polycarbonate capacitors except for the temperature limitation of 85°C.

2.2 D.C. Filter

The large size and weight of polycarbonate film capacitors compared with tantalum electrolytics, as indicated in section 1.3.3 of this report, make this type of capacitor unattractive for a D.C. filter application.

A few of two types of tantalum capacitors were purchased for experimental testing.

The rating of the sintered tantalum capacitors purchased is 22 microfarads, 100 Volts D.C., 125°C.

Tantalum foil electrolytic capacitors purchased have a rating of 36 microfarads, 150 Volts D.C. at 125°C temperature.

Voltage ratings greater than 100 Volts D.C. for sintered tantalum electrolytics are available by series element arrangements with associated penalties in size and weight.

Aluminum electrolytics were not considered because of the 65°C temperature limitation.

3.0 Experimental Tests

3.1 Objectives

Capacitors will be subjected to experimental tests to obtain data and characteristics to accomplish the following:

*Trademark of the E. I. DuPont Co.

A) Establish capacitor A.C. characteristics, ratings and limits for such factors as safe operating voltage, temperature rise, frequency, reliability and life as effected by environment for application to circuits in aerospace inverters and converters.

B) Recommend selection of proper capacitor type to facilitate minimum size and weight and maximum performance and reliability of inverters and converters.

3.2 Description of Tests

There are two parts to the experimental testing planned. The first part will be to determine the A.C. characteristics of the capacitors.

The second part is to determine capacitor reliability factors, from accelerated life testing, within the scope of this study.

To determine the A.C. characteristics of the capacitors, bridge measurements will be made to obtain power factor as a function of frequency and temperature. Capacitor power factor values that approach the accuracy of the bridge can be verified by energizing the capacitors with sinusoidal voltages and power losses measured by a calorimeter.

Next the capacitor power losses will be determined while the capacitors are in a calorimeter and energized in inverter circuits.

Correlation factors relating measured capacitor power losses are expected to be obtained. Correlation between capacitor power losses calculated from the product of capacitor power factor, obtained with sinusoidal voltage measurements, and calculated rms currents contained in Appendix B, and losses measured while operating in inverter circuits. These correlation factors for power losses will facilitate proper selection of capacitors and ratings for application in aerospace inverters and converters by equipment designers.

Accelerated life testing will include overvoltage and overtemperature testing to obtain information relating to safe operating voltage and temperature consistent with life objectives.

4.0 Work Planned for Next Quarterly Report Period

It is planned to complete the first part of the experimental tests, that of obtaining the A.C. characteristics of the capacitors, during the next quarterly report period.

5.0 CONCLUSIONS

A) Metallized polycarbonate film capacitors are approximately 25 per cent larger than equivalent metallized paper capacitor ratings.

B) The lack of adequate A.C. data and characteristics of capacitors was indicated by non-duplication of recommended capacitor size and type, by vendors, for any capacitor specified.

APPENDIX A

CAPACITOR RATINGS USED IN SURVEY

1. Commutating Capacitors

Capacitance (MFD)	5	5	5	15	15	15	50	50	50
Max.Steady State DC Volt.	35	65	105	35	65	105	35	65	105
Peak Trans.DC Voltage	52	97	157	52	97	157	52	97	157
Peak Amps.@S.S.Voltage*	4.6	8.6	11	13.8	26	33	46	86	110

*Commutating current pulses are one quarter sine wave with a frequency of 3.46 KC and repetition rate of 400 CPS

2. AC Filter Capacitors

Capacitance (MFD)	1-3	1-3	8-10	8-10	50-60	50-60
Voltage RMS, 420 CPS	135	270	135	270	135	270
5 Cycle Surge Volt.RMS	170	340	170	340	170	340
Dielectric DC Volt.Rating	600	1000	600	1000	600	1000

3. DC Filter Capacitors

Capacitance (MFD)	1000-1500	1000-1500	1000-1500	10,000-15,000	10,000-15,000	10,000 15,000
DC Working Voltage	35	65	105	35	65	105
100 M Sec. Surge Voltage	52	97	157	52	97	157
Peak to Peak Ripple Volt.**	3.5	6.5	10.5	3.5	6.5	10.5

**Ripple voltage of half sine wave pulses having frequencies up to 25 KC with a repetition rate of 2.5 KC.

APPENDIX B

CAPACITOR RMS CURRENT AND VOLTAGE CALCULATIONS

1. Commutating Capacitors

The current waveshape for the commutating capacitors is shown in Figure 1.

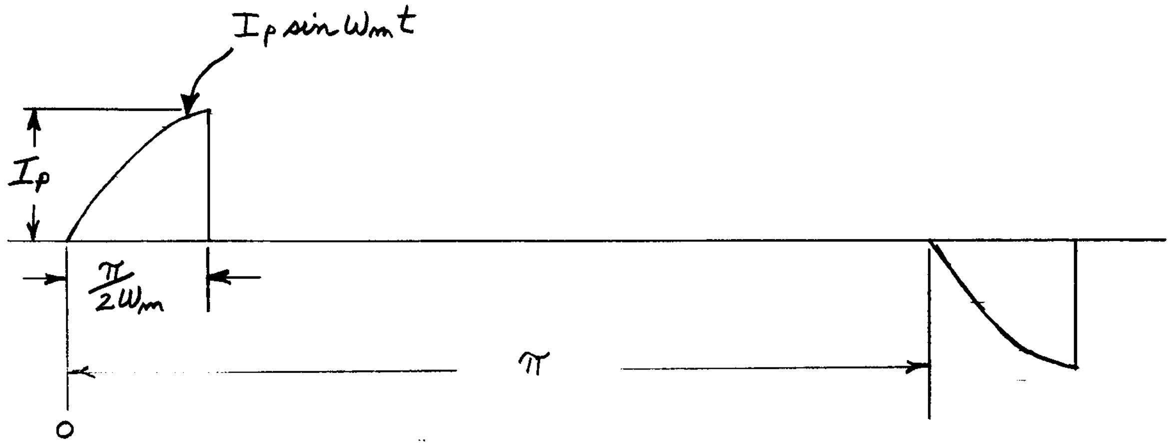

FIGURE 1

The effective value of current or RMS value may be determined from the following:

$$I^2\ \text{rms} = \frac{1}{T}\int_0^T i^2 dt \qquad \text{where } i = I_p \sin \omega_m t$$

$$I^2\ \text{rms} = \frac{I_p^2 \omega_o}{\pi}\int_0^{\frac{\pi}{2\omega_m}} (\sin^2 \omega_m t)\, dt \qquad \text{where } f_o = 400 \text{ CPS}, \quad f_m = 3.46 \text{ Kc}$$

$$= \frac{I_p^2 \omega_o}{\pi}\int_0^{\frac{\pi}{2\omega_m}} \left(\tfrac{1}{2} - \tfrac{1}{2}\cos 2\,\omega_m t\right) dt$$

$$= \frac{I_p^2 \omega_o}{\pi}\left[\frac{\pi}{4\omega_m} - \sin 2\frac{\omega_m \pi}{2\omega_m}\right]$$

$$I^2_{rms} = \frac{I_p^2 \omega_o}{4 \omega_m} = \frac{I_p^2 \; 400}{4 \; (3460)} = \frac{I_p^2}{34.6}$$

$$I_{rms} = I_p \sqrt{\frac{1}{34.6}} = 0.17 \; I_p$$

Information obtained in the survey indicates that polycarbonate film capacitors have a relatively constant power factor over a large frequency range. If this is verified in the experimental tests, then capacitor losses may be calculated from the product of the squared value of the rms current and the capacitor effective series resistance (ESR). The ESR may be determined from bridge power factor measurements.

If the power factor for polycarbonate film capacitors is found to vary considerably with frequency in the experimental tests, a Fourier analysis of the waveform may be necessary to obtain the significant harmonic currents and voltages. A more consistent correlation with the product of these voltages, currents and capacitor power factors at these frequencies to actual power losses may be available with this approach.

2. DC Filter Capacitors

The voltage waveform impressed on DC filter input capacitors in aerospace inverters is of the following form:

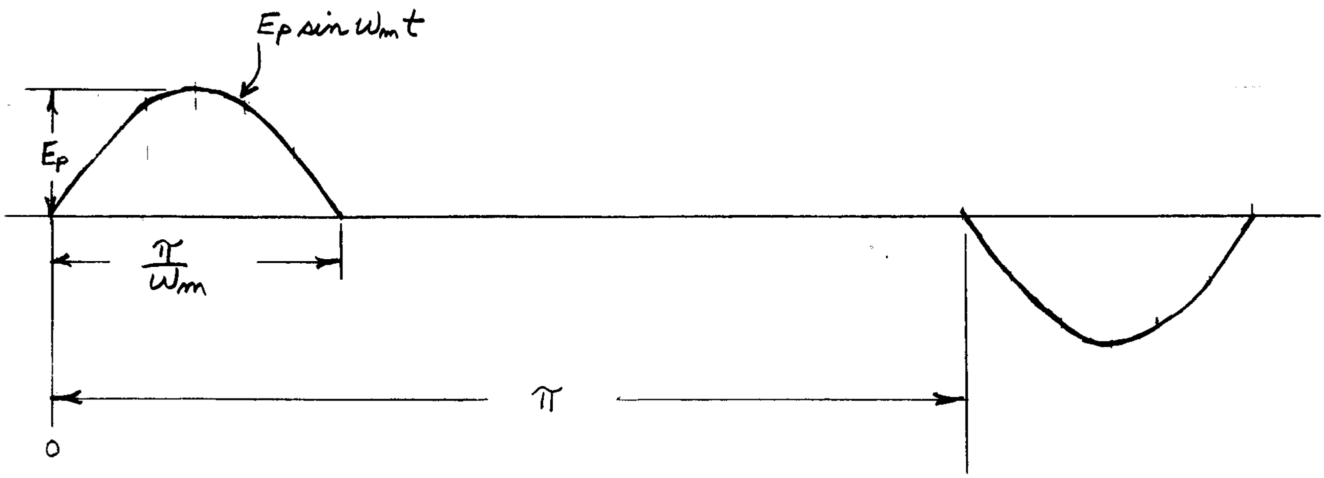

FIGURE 2

The effective value or RMS voltage is determined in the following manner:

$$E^2 rms = \frac{1}{T}\int_0^T e^2 dt \quad \text{where } e = E_p \sin \omega_m t,\ f_m = 25\ K_c,\ f_o = 2.5\ K_c$$

$$E^2 rms = \frac{2\,\omega_o E^2}{\pi}\int_0^{\frac{\pi}{2\omega_m}} (\sin^2 \omega_m t)\, dt$$

$$E^2 rms = \frac{2\,\omega_o E_p^2}{\pi}\int_0^{\frac{\pi}{2\omega_m}} \left(\tfrac{1}{2} - \tfrac{1}{2}\cos 2\,\omega_m t\right) dt$$

$$E^2 rms = \frac{2\,\omega\, E_p^2}{\pi}\left[\frac{\pi}{4\,\omega_m}\right] = \frac{E_p^2\omega_o}{2\,\omega_m} = \frac{E_p^2}{20}$$

$$E\ rms = E_p\sqrt{\frac{1}{20}} = 0.224\ E_p$$

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